Trip B-7

PROGRESSIVE METAMORPHISM IN DUTCHESS COUNTY, NEW YORK

A. E. Bence
SUNY - Stony Brook

and

J. M. McLelland
Colgate University

1. Introduction

The purpose of this trip is to examine the development of regional progressive metamorphism within southeastern Dutchess County, N.Y. All stops, except the first, lie within the Clove 15' quandrangle (Fig. 1). Localities to be visited have been chosen in order to show a variety of mineral assemblages beginning with rocks at chlorite grade and proceeding eastward through the first sillimanite isograd. The majority of lithologies to be examined are pelitic with interbedded cherts and quartzo-feldspathic rocks. One stop will be made within units of the carbonate shelf sequence where calc-silicates may be seen. The implications of recent geochronological studies will be discussed relative to the geologic history of the area.

2. Previous Work

The general area attracted a number of early workers--e.g. Berkey (1907), Knopf (1927). Modern investigations began with the classic studies of Balk (1936) and Barth (1936). Their research of the structural geology and petrology of Dutchess County laid a groundwork that continues to serve as an important guide for present day investigations. To a large extent, the general geology shown in Figs. 1 and 2 is a result of their mapping. Barth's delineation of several isograds, and his petrochemical work, have provided an early framework from which modern petrological research has been able to build.

In recent years the metamorphic petrology of the Dutchess County area has been studied by Bence (1971) and Vidale (1974a,b; 1975). On the basis of microscopic examination, Vidale (1974a) moved Barth's (1936) isograds farther to the west. Bence (1971) determined a similar set of isograds, and these are shown in Fig. 2.

Vidale (1974b, 1974c) studied the nature and origin of veins and vein assemblages in the pelitic rocks of the area. Her results indicate that the vein assemblages: quartz, quartz-calcite, quartz-plagioclase, and quartz-plagioclase-orthclase form at successively higher grades and are probably derived from the surrounding matrix.

Recent field mapping has been undertaken within the Harlem Valley area (McLelland and Fisher, this volume) and within a large area to the west of the Clove 15' quadrangle (Fisher and Warthin, this volume).

Geochronologic studies in the region have been conducted by Clark and Kulp (1968), Long (1969), Long and Kulp (1962), Ratcliffe (1968), Bence and Rajamani (1972) and Mose et al. (1976). Some of these results will be discussed in Section 8 of this paper.

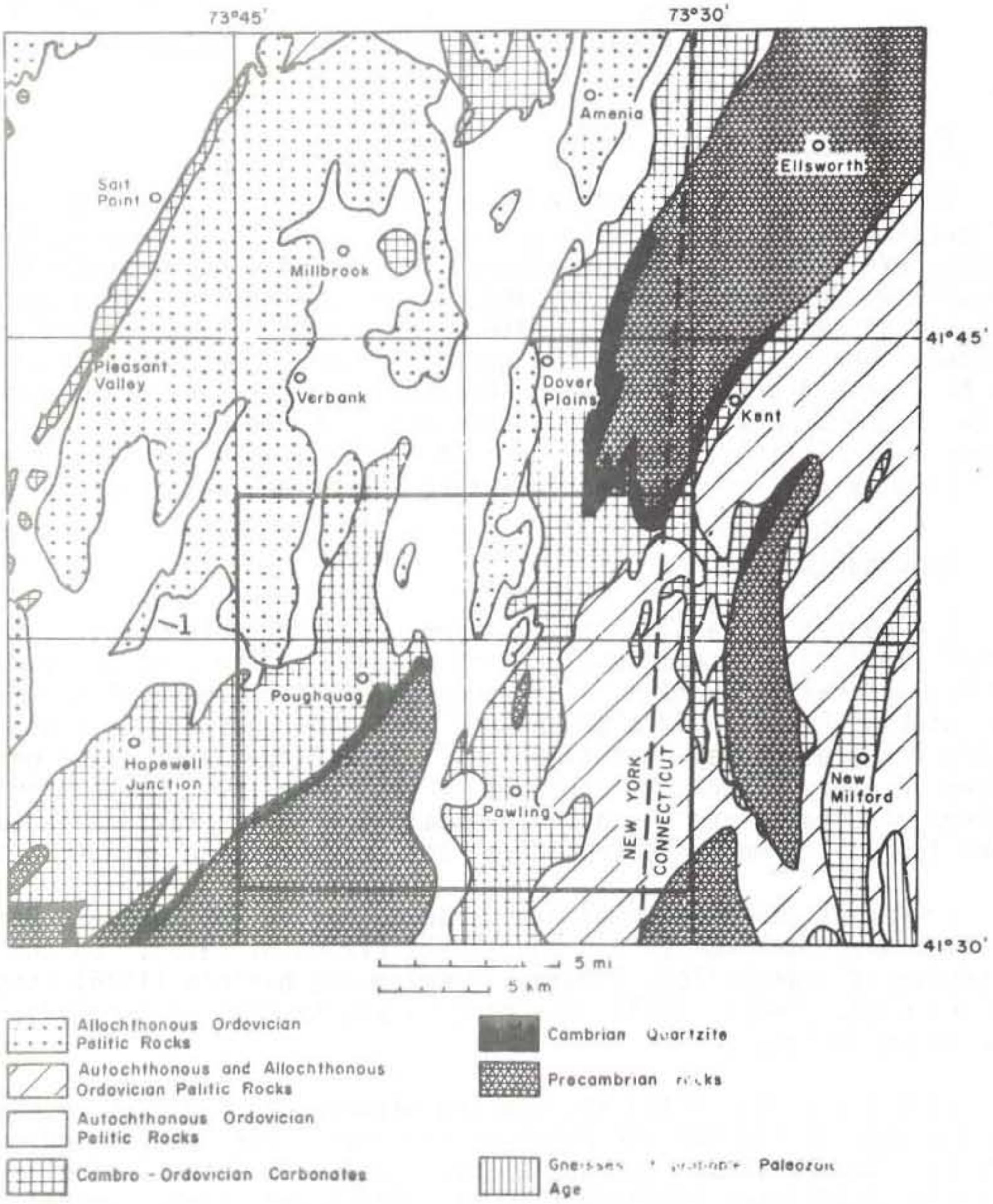


Fig. 1. Generalized Geological map of the Dutchess County region. Location of 7 1/2' quadrangles indicated by town names. The Clove 15' quadrangle includes the following 7 1/2' quadrangles: Verbank, Dover Plains, Poughquag, and Pawling. The area enclosed by the heavy dark line is enlarged in Fig. 3. Stop 1 is identified by the number 1. (After N.Y. State Geological Map, 1973)

3. Stratigraphy and Synopsis of Geologic History

Within the Taconic region stratigraphic relationships have proven to be extremely important in working out the structural relationships of complexly deformed rocks. From the petrological point of view, knowledge of stratigraphy is helpful in relating metamorphism to the regional structural framework and to parent lithologies. We therefore present a brief synopsis of the stratigraphy relevant to the area and its relationship to the regional geologic history as currently understood.

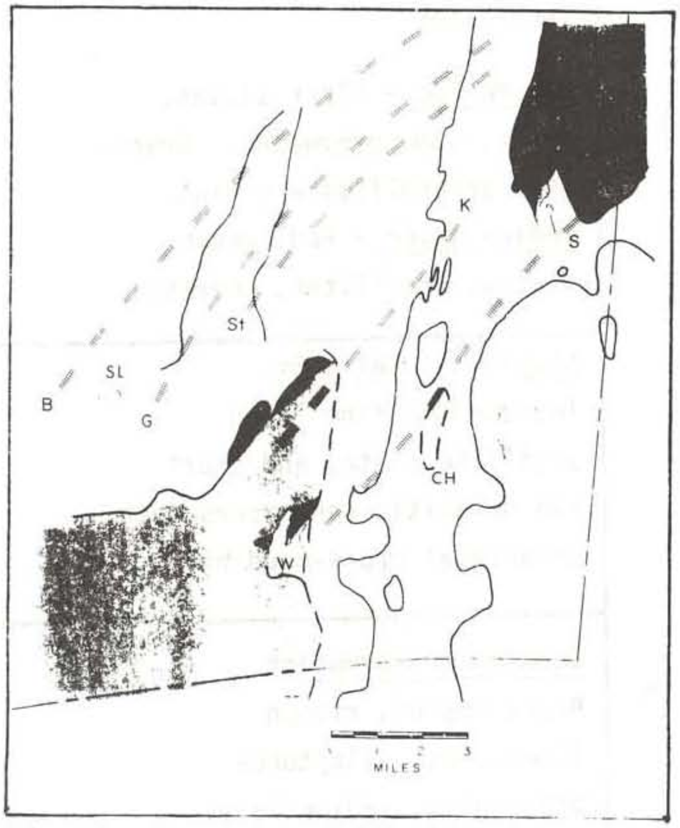
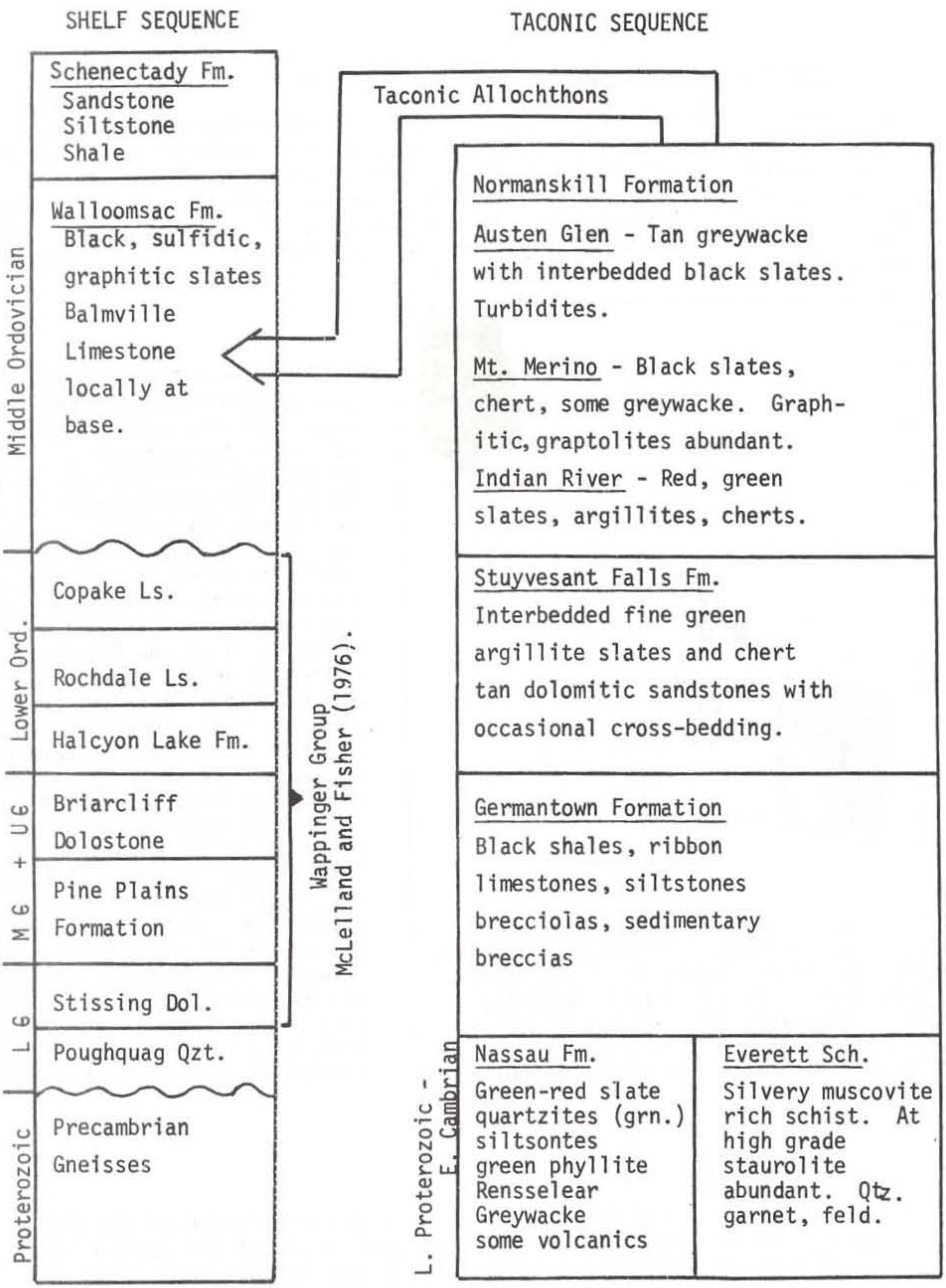


Fig. 2. Isograds: B-biotite, G-garnet, St-staurolite, K-kyanite, S-sillimanite. Locations: SL-Sylvan Lake, W-Whaley Lake, CH-Corbin Hill. Cambrian qzt.-black; Precambrian gn.-dark grey; pelites-stipple at margins; carbonates-unpatterned.

Four general lithologies are easily recognizable within the area: (1) Precambrian gneisses; (2) an orthoquartzite; (3) carbonates; and (4) pelitic masses. No internal stratigraphy has been worked out for the local Precambrian gneisses. The orthoquartzite is of lower Cambrian age and rests unconformably on the Precambrian basement. It is referred to as the Poughquag Quartzite and is correlative with the Hardyston, Potsdam, Lowerre, Chesire, etc. Above the Poughquag Quarzite occurs the carbonate sequence. Its internal stratigraphy has been determined throughout much of the area and is discussed by McLelland and Fisher (this volume). All but one of the carbonate units (Balmville Limestone) lie within the Wappinger Group (= Stockbridge Group). The Poughquag Quartzite and Wappinger carbonates form part of the Cambrian and Early Ordovician shelf that occurs throughout eastern North America.

The success in stratigraphic subdivision and correlation of the shelf carbonates has not been duplicated in the case of all of the pelitic units. To the west Fisher and Warthin (this volume) have established a coherent and detailed stratigraphy within the pelites. However, eastward increases in metamorphic grade have obscured fossil evidence, color differences, and other characteristics that have been utilized for correlation and subdivision



SHELF SEQUENCE

Middle Ordovician

Schenectady Fm.
Sandstone
Siltstone
Shale

Walloomsac Fm.
Black, sulfidic, graphitic slates
Balmville Limestone locally at base.

Lower Ord.

Copake Ls.

Rochdale Ls.

Halcyon Lake Fm.

M G + U G

Briarcliff Dolostone

Pine Plains Formation

L G

Stissing Dol.

Poughquag Qzt.

Wappinger Group
McLelland and Fisher (1976).

Proterozoic

Precambrian Gneisses

TACONIC SEQUENCE

Taconic Allochthons

Normanskill Formation

Austen Glen - Tan greywacke with interbedded black slates. Turbidites.

Mt. Merino - Black slates, chert, some greywacke. Graphitic, graptolites abundant.

Indian River - Red, green slates, argillites, cherts.

Stuyvesant Falls Fm.
Interbedded fine green argillite slates and chert tan dolomitic sandstones with occasional cross-bedding.

Germantown Formation
Black shales, ribbon limestones, siltstones brecciolas, sedimentary breccias

L. Proterozoic - E. Cambrian

Nassau Fm.
Green-red slate
quartzites (grn.)
siltsontes
green phyllite
Rensselear
Greywacke
some volcanics

Everett Sch.
Silvery muscovite rich schist. At high grade staurolite abundant. Qtz. garnet, feld.

Table 1. Stratigraphic Relationships, Dutchess Co., N.Y.

in other areas. Table 1 summarizes the stratigraphic relationships as established in low grade, metamorphic terrains. Following Rickard and Fisher (1973), we have restricted the term Normanskill Formation to Taconic Sequence rocks.

(a) Evolution of the Shelf Sequence

The geologic evolution of the Shelf Sequence is relatively well understood. As shown in Table 1, the shallow water carbonates of the Wappinger Group are terminated upwards by an unconformity related to the early Middle Ordovician breakup of the shelf. Following erosion, a basal limestone (Balmville) and black, graphitic shales of the Walloomsac Formation (Zen, 1963) were deposited in a deepening Middle Ordovician exogeosyncline (Martinsburg - Snake Hill Exogeosyncline, Rickard and Fisher, 1973). Within upper Middle Ordovician time sandstones and siltstones of the Schenectady Formation were deposited.

(b) Evolution of the Taconic Sequence

The sedimentological history of the Taconic Sequence is less certain than that of the shelf rocks. It is believed that the Taconic Sequence formed in the general vicinity of the continental slope and rise. Beginning in late Precambrian, or Eocambrian, time the opening of Iapetus was accompanied by the deposition of clastics off the eastern margin of North America. These are now represented by the Nassau Formation and its possible correlative, the Everett Schist. The Everett may have been deposited farther out on the continental rise than the Nassau. In Cambrian time the earlier deposits were blanketed by black shales, ribbon limestones, and sedimentary breccias of the Germantown Formation (= West Castleton and Hatch Hill Formations). This unit built up a continental slope down which slumping and gravity sliding took place and gave rise to brecciolas, conglomerates, and various sedimentary structures. The carbonate in the limestone lithologies was presumably provided by lime muds moving down from the developing carbonate shelf. The Germantown Formation is followed upward by a sequence of shales, cherts, and thin dolomitic sands known as the Stuyvesant Falls Formation (= Poultney Slates). These units continued to build up the slope and probably extended out onto the rise.

Following deposition of the Stuyvesant Falls Formation, breakup and erosion of the shelf began in lower Middle Ordovician time. Subsequently, red and green shales and argillites of the Indian River member of the Normanskill Formantion were deposited. These distinctive units were followed upward by black shales and cherts of the Mt. Merino member. Above these were deposited the greywackes and black shales of the Austen Glen member. Rickard and Fisher (1973) place the time of the final deposition of the Austen Glen in the middle of graptolite zone 12 of the lower Middle Ordovician. This places Austen Glen deposition prior to the deposition of the Balmville Limestone and lower Walloomsac black shales. Others (Zen, 1963; Bird and Dewey, 1975) have considered the Austen Glen to be of younger age. The present authors remain agnostic on this controversy and only wish to establish the general stratigraphic relationships of the area.

Within lower Middle Ordovician time (graptolite zone 13), the Taconic Sequence was emplaced westward as submarine gravity slides within the Martinsburg-Snake Hill exogeosyncline. Several of these slides have been recognized in western Dutchess County (Fisher and Warthin, this volume) and allochthonous Taconic Sequence rocks are well exposed along the Taconic Parkway (Stop 1). The early gravity slides were followed by thrust slices of lithified Everett Formation, some low grade representatives of which are recognizable near Millbrook, Verbank, and on the western margin of the Clove Valley (Fig. 1).

Following emplacement of the allochthonous masses, the area was tightly folded and metamorphism overlapped late phases of the regional deformation. Isograds related to this thermal peak trend NNE across the area. The basically contemporaneous nature of the deformation and metamorphism is borne out by fabric-mineral relationships and by geochronological results to be presented in a later section. In thin section, micaceous minerals lie parallel to early foliations and have been kinked by a late deformation. Chloritoids grow across early foliations but have been deformed by kinking. Staurolite grains grow across all deformational fabrics and garnets appear to have grown throughout much of the later deformation.

4. Special Stratigraphic-Structural Problems

Within the area bounded by the Clove 15' quadrangle, and particularly east of the Clove Valley, high metamorphic grade has made it difficult to subdivide the pelitic units. East of the biotite isograd only three broad stratigraphic categories of metapelitic units have been utilized. As shown on the 1973 edition of the New York State Geological Map these are the Walloomsac, the Everett Schist, and the Manhattan Fm. The Walloomsac is characterized by black, graphitic schists rich in biotite. At its base it grades into the thin Balmville limestone. The Everett Schist is generally more aluminous than the Walloomsac and, as a consequence, is richer in muscovite and staurolite. The Manhattan Formation contains lithologies that correspond to both the Walloomsac and Everett.

In Figures 2 and 3, we have generally followed the 1973 edition of the New York State Geological map in designating schist masses as Walloomsac, Everett, or Manhattan. The structural implications of such designations are considerable, because the Walloomsac is thought to be autochthonous, the Everett alochthonous, and the Manhattan may be either. These designations will almost certainly undergo changes in the future. For example, the various schist masses may be internally divided on the basis of high versus low aluminum content, and further research along such lines appears promising. In the meantime, the 1973 New York State Geological Map continues to serve as a standard reference for stratigraphic assignment of the metapelites. Note that schists currently mapped as Everett may possibly contain metamorphosed equivalents of younger Taconic Sequence rocks (i.e. Normanskill, Germantown, Stuyvesant Falls).

5. Folds and Related Cleavages

As in other regions of Taconide Zone, the area has been affected by intense, polyphase deformation. This complex tectonism is reflected by the minor structures that appear in almost every outcrop. Where mapping has revealed major structures they too reflect a history of intense deformation. However, the lack of stratigraphic control within the pelitic units has presented recognition of regional fold patterns to the extent shown by Fisher and Warth (this volume) is similar, but relatively unmetamorphosed, rocks to the west (1976).

(a) Major Folds

Recent work (McLelland and Fisher, this volume) has demonstrated that the entire carbonate sequence underlying the Harlem Valley is overturned to the west and represents the eastern limb of a major NNE syncline (Harlem Valley Syncline). The Housatonic Highlands may represent part of an eastern anticlinal counterpart to this syncline, and the Hudson Highlands may occupy a similar anticlinal structure to the west. The Harlem Valley Syncline is believed to be a second generation Taconian structure that post-dated the emplacement of the allochthons.

The axial trace of the Harlem Valley Syncline passes through the schists lying along the western margin of the Harlem Valley. Continued westward, these rocks lie on the right-side-up, western limb of the syncline. The structure is abruptly terminated by the Precambrian gneisses forming the northern prong of the Hudson Highlands (Fig. 3). Along the eastern contact of this prong, Paleozoic schists rest on top of Precambrian gneisses or Poughquag Quartzite. The Wappinger Group, which should reappear on the western limb of the Harlem Valley Syncline, is completely absent. This discontinuity may be explained by normal faulting, reverse faulting, or the early Middle Ordovician unconformity. The second possibility was favored by Balk (1936) and is supported by minor structures (drag folds, lineations) and by demonstrated westward directed reverse faults near Whaley Lake. Following Balk (1936), we have shown this Precambrian-Paleozoic contact as a reverse fault on Fig. 3.

Within the Clove Valley the carbonate sequence and Walloomsac Slates appear to be right side up but no major fold structure has yet been mapped within these carbonates.

The dominant pervasive cleavage of the region is axial planar to folds of the set represented by the Harlem Valley Syncline. Microscopically this cleavage is represented by strong orientation of platy minerals. It is believed that the folding represents the major deformational pulse of the Taconic Orogeny following the emplacement of allochthonous masses.

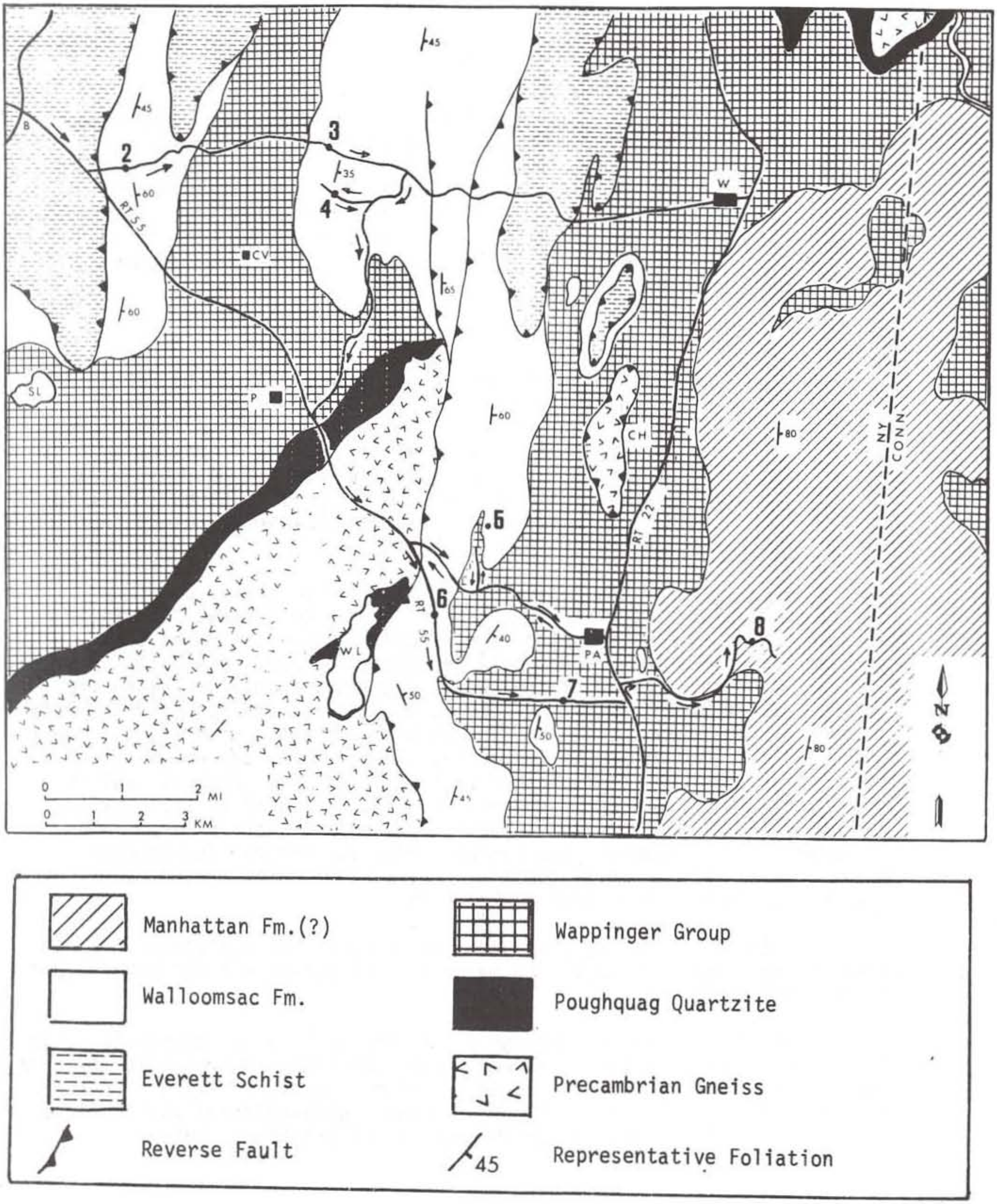


Fig. 3. Enlargement of rectangular area outlined in Fig. 1. Trip route and Stops 2-8 shown. Geology after Balk (1936) and New York State Geological Map (1973). SL-Sylvan Lk., WL-Whaley Lk., B-Billings, W-Wingdale, P-Poughquag, PA-Pawling, CV-Clove Valley, CH-Corbin Hill.

(b) Minor Structures

The metapelitic rocks of the area are replete with excellent minor structures. Early tight folds, kink folds, a variety of cleavages, boudinage, etc. are all recognizable. At least three, and perhaps four, folding events appear to be present in many outcrops. The earliest of these is represented by isoclinal folds usually defined by quartzose layers. These, and an associated early foliation, have been folded about tight NNE folds that are correlated with the event represented by the Harlem Valley Syncline. The dominant cleavage of the region is axial planar to these folds. Following the early episodes of tight folding, a kinking developed in pelitic units and an open, assymetric folding took place in more massive lithologies. The kinking is accompanied by excellent crenulation cleavages. The majority of structures of this type trend approximately NE, but variability is present and may reflect more than a single episode of kink folding.

It is possible that the earliest recognizable fold event was preceded by a still older deformation. This is suggested by the fact that the earliest recognized isoclinal folds occasionally have mica flakes that wrap around early hinges. However, caution must be exercised in interpreting this sort of feature which may be due to mimetic recrystallization of original bedding plane foliation.

Microscopically, foliations associated with the early folds are best represented by aligned micas. Occasionally a microscopic fold may also be seen. Generally these are of the second generation and micas of the first generation event have been rotated abou the later fold hinges. Later kinking and crenulation cleavage is beautifully displayed in most sections. As previously mentioned in Section 3b, all of these fabrics precede the higher grades of metamorphism, i.e. the growth of staurolite and sillimanite.

6. Precambrian Massifs

The two major Precambrian massifs in the area are the Housatonic Highlands and the portions of the eastern Hudson Highlands. Some uncertainty exists with regard to whether or not these masses are anticlinoria rooted at depth or represent thrust sheets (Isachsen, 1964; Harwood and Zeitz, 1974). Field relationships suggest that a rooted hypothesis is likely, although significant reverse faults have caused slivers of the Precambrian to be thrust westward. Faults of this nature have been demonstrated within the Housatonics (Balk, 1936) and in the vicinity of Towners, N.Y. (McLelland and Fisher, this volume). The Precambrian outlier at Corbin Hill in the Harlem Valley appears to be a klippe resting on top of the carbonate shelf sequence (McLelland and Fisher, this volume). In none of these instances has it yet been possible to determine the amount of offset.

7. Metamorphism of the Pelitic Rocks

Early structural and petrographic studies by Balk (1936) and Barth (1936) reveal that mineral assemblages in the pelitic schists reflect a regional metamorphic gradient in which intensity increased from WNW to ESE. The gradient is from chlorite through to sillimanite-K-feldspar zones which is typical of the kyanite-sillimanite facies series of Miyashiro (1961).

Two distinctly different bulk compositions are recognized in the low-grade slates and phyllites and high-grade schists from Dutchess County: (1) an aluminous composition whose assemblage is dominated by muscovite, and (2) an aluminum-poor, graphitic composition characterized by abundant biotite, graphite, and iron sulfides. Both compositions can be traced to the highest metamorphic grades, although phase compositional data are not yet available for both compositions at all grades.

At grades below the stability field of biotite, the phyllites and slates are dominated by aluminous, iron-rich chlorite; quartz; phengitic muscovite; and alkali (sodic) feldspar (Stop 1) (Table 2). Ilmenite, which is abundant in the aluminous composition, has, at some localities, altered to leucoxene.

The first appearance of biotite (Stop 2) appears to be a consequence of the reaction of iron-rich chlorite and phengitic muscovite to form iron-biotite; a more magnesian chlorite; and a more sodic, less phengitic muscovite. At the same time, the feldspar has become more calcic (Table 2). At one locality (Stop 3), characterized by very highly aluminous compositions, chloritoid appears prior to the appearance of biotite, and the assemblage chloritoid + chlorite + muscovite + feldspar + ilmenite + quartz is observed.

The appearance of garnet (Stop 3) is reflected by sharp discontinuities in the compositions of the muscovite and the feldspar. The mica becomes much more sodic and the feldspar more calcic (Table 2). The garnet itself is concentrically zoned. Its core contains a large spessartine component (Table 2 and Fig. 4) which drops off markedly towards the rim. Presumably this zoning reflects the growth rate of the garnet and the diffusion rate of components through the matrix at the time of garnet growth. The shape of the MnO profile suggests that garnet growth follows a Rayleigh depletion model (see Hollister, 1966).

At this grade of metamorphism, the aluminum-rich and aluminum-poor bulk compositions are readily distinguished by the presence of either biotite or chloritoid in the assemblage (Fig. 5a). At slightly higher metamorphic grades there occur a complex sequence of reactions (Fig. 5b) involving the breaking of the chlorite-garnet join on the AKFM projection; the breakdown of chloritoid; and the appearance of staurolite (see Albee, 1973).

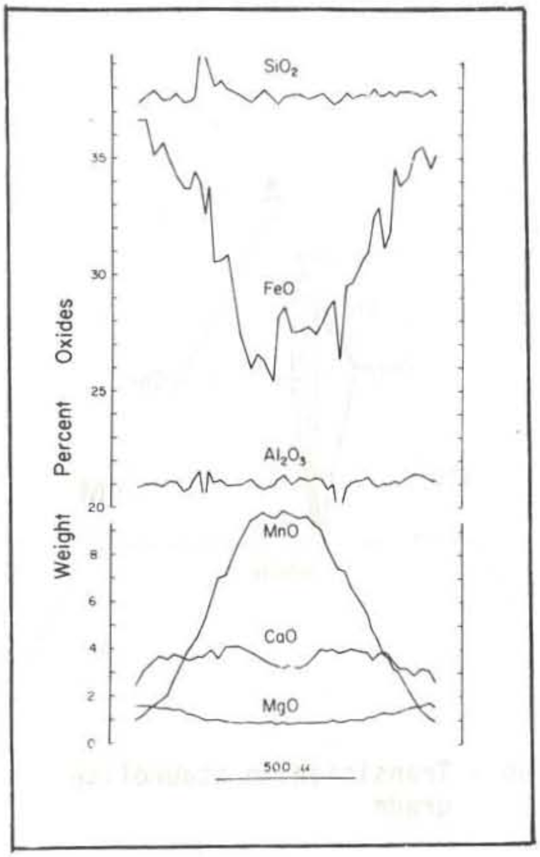


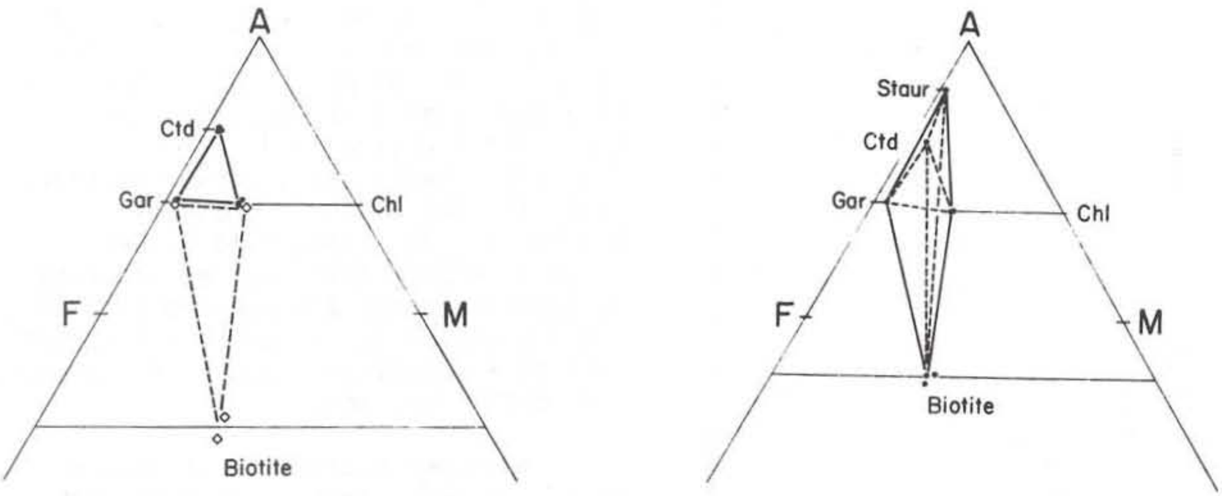
Fig. 4. Electron microprobe traverse across a garnet from Dutchess County. Note the bell shaped profile of MnO. Sample collected from Stop 3.

In the Dutchess County schists one locality has been found (Stop 4) in which the minerals staurolite-chloritoid-garnet-biotite-chlorite (Table 2) (Fig. 5b) are all observed in the same thin section. This clear violation of the Phase Rule appears to be a consequence of reaction kinetics. The first reactions did not go to completion before subsequent reactions involving the daughter products commenced. At metamorphic grades slightly higher than that at locality 4, chloritoid has disappeared (Stop 5), and the assemblage staurolite + garnet + biotite + muscovite + quartz is observed (Table 2) (Fig. 5c).

At grades equivalent to Stop 5 (e.g. Stop 6), kyanite coexists with garnet and biotite (Table 2). As shown in Fig. 4c the development of kyanite rather than staurolite may be due to the FeO/MgO of the original sediments. Rarely kyanite and staurolite (with biotite and garnet) are observed in the same thin section. This assemblage violates the Phase Rule and indicates a lack of attainment of chemical equilibrium. Staurolite is not observed in higher grade rocks, and it is likely that its occurrence in the kyanite-bearing assemblages marks the upper limit of its stability field.

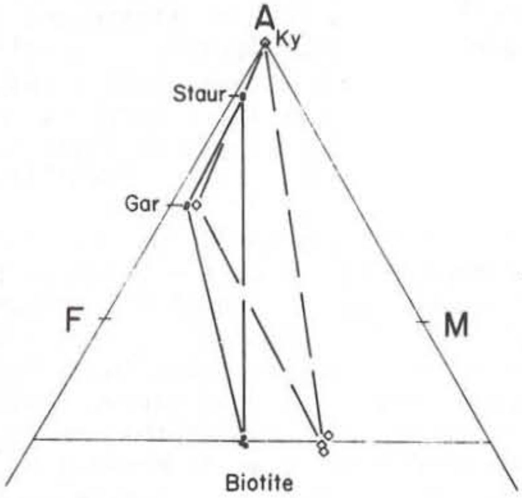
Sillimanite is present in the eastern schist masses of Dutchess County and has formed by three reactions: (1) kyanite → sillimanite (lowest grade appearance), (2) staurolite + Na-muscovite ($Mu_{82}Pg_{18}$) + quartz → sillimanite + K-rich muscovite ($Mu_{95}Pg_{5}$) + albite + biotite + garnet + H_2O (see Guidotti, 1970), and (3) a complicated reaction relationship involving the breakdown of biotite adjacent to garnet prophyroblasts in garnet-biotite-muscovite schist. The polymorphic transition (1) suggests that pressures in excess of about 5 kb obtained if the triple point as determined by a Richardson et al. (1968) is appropriate. In all cases sillimanite occurs as fibrolite.

At the highest metamorphic grade observed in Dutchess County, muscovite is absent and sillimanite and K-feldspar coexist. These assemblages occur sporadically near the Connecticut state line where they are surrounded by muscovite-bearing assemblages. This suggests that the reaction surfaces are relatively flat lying in this region with that of muscovite + quartz sillimanite + K-feldspar + H_2O nearly coincident with the present erosion surface.



5a - Garnet-biotite grade

5b - Transition to staurolite grade



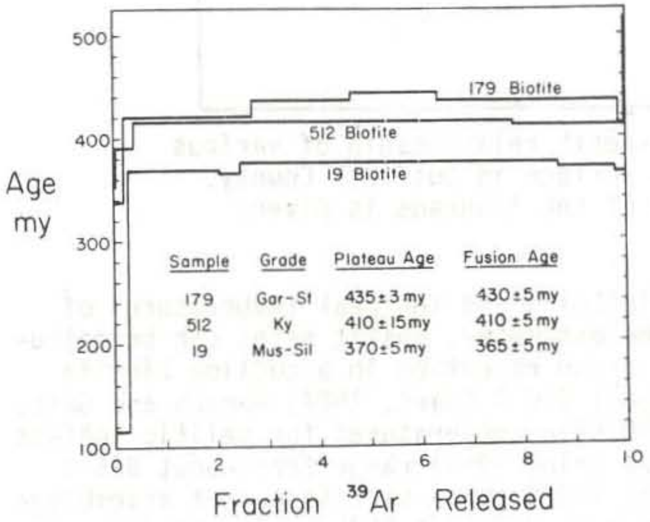
5c - Kyanite grade

Fig. 5. AKFM projections at several grades of metamorphism.

8. Geochronology

Whole-rock and mineral istopic ages from the pelitic schists of Dutchess County (Long, 1962) were interpreted to indicate a period of metamorphism at 430 m.y. ago (minimum age) followed by a regional thermal event about 360 m.y. ago. These ages are consistent with the Taconic and Acadian orogenies, respectively. Toward the south and east, K-Ar ages ranging from 480 m.y. to 240 m.y. suggest that three distinct metamorphic events of 460-480, 360, and 255 m.y. affected the region (Clark and Kulp, 1968). In the region between Bridgeport and New Haven, Connecticut, K-Ar ages of 220-280 m.y. are reported (Clark, 1966; Armstrong et al., 1968). These younger ages are thought due to reheating or uplift during the Alleghany orogenic period (Dieterich, 1968).

$^{40}Ar/^{39}Ar$ incremental heating "ages" obtained by Bence and Rajamani (1972) on biotite and muscovite separates from five localities in Dutchess County suggest that metamorphic recrystallization and argon diffusion in this region did not occur in two discrete thermal events. All the samples studied had less than two percent argon loss and, consequently, give well-defined plateau "ages" which range from 435 to 370 m.y. (Fig. 6). A direct correlation between increasing metamorphic grade and decreasing gas-retention "age" is noted. If the processes that caused argon loss during the metamorphism are reproduced during the incremental heating of the sample in the vacuum furnace (Hanson et al., 1975), then these ages are most easily explained by continuous rather than episodic argon loss and probably reflect cooling during essentially continuous uplift following the Taconic orogeny. There appears to be no need for a distinct Acadian thermal event to explain the metamorphic recrystallization. This conclusion is consistent with recent Rb/Sr studies by Mose et al. (1976) in the vicinity of Peekskill, N.Y.



Sample	Grade	Plateau Age	Fusion Age
179	Gar-St	435±3 my	430±5 my
512	Ky	410±15my	410±5 my
19	Mus-Sil	370±5 my	365±5 my

Fig. 6. Argon loss and plateau "ages" for biotites from 3 metamorphic grades in Dutchess County.

If this interpretation of the $^{40}Ar/^{39}Ar$ ages is correct, then a model involving differential uplift is required (Fig. 7). Furthermore, if gas-retention temperatures for biotite and muscovite, the geothermal gradient

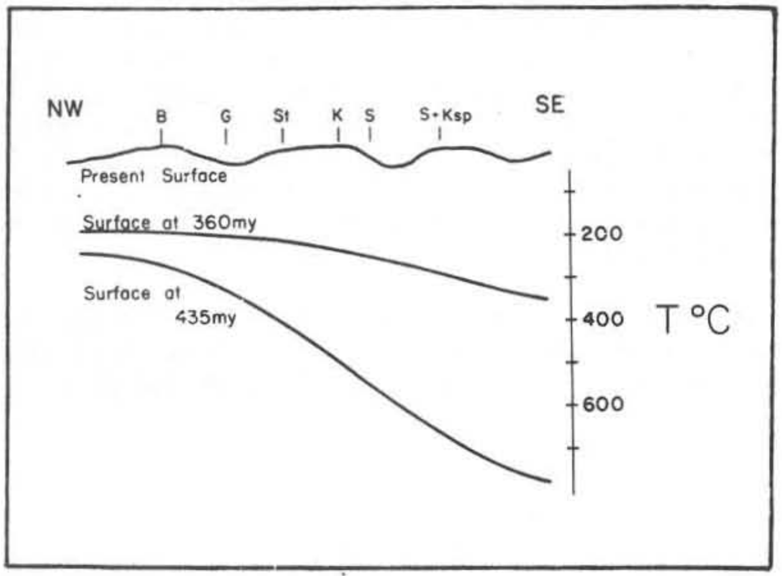


Fig. 7. Temperature-depth relationship of various ages for present day surface in Dutchess County. Approximate location of the isograds is given.

for the region during the lower Paleozoic, and the peak temperatures of metamorphic recrystallization can be estimated, uplift rates can be calculated. Under geologic conditions, argon retention in a cooling biotite occurs at temperatures less than about 300°C (Hart, 1964; Hanson and Gast, 1967; Jaeger et al., 1967). $^{18}O/^{16}O$ paleotemperatures for pelitic schists from Dutchess County (Garlick and Epstein, 1967) range from about 625°C for sillimanite grade assemblages to 480°C for a biotite-garnet assemblage collected at Stop 3. If a geothermal gradient of 25°C/km is assumed, a maximum continuous uplift rate of ~1/3 cm/year is obtained from the sillimanite grade rocks. This uplift rate appears unusually slow and should have resulted in extensive retrograde metamorphism. This apparent discrepancy suggests that the implied assumption that argon diffusion and oxygen isotope equilibration occurred at the same time is not correct.

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Table 2

	Chlorite Grade		*Biotite Grade*		*Garnet Grade*	
ALUMINOUS ASSEMBLAGES	Muscovite	$Ms_{95}Pg_5$	Muscovite	$Ms_{80}Pg_{20}$	Muscovite	$Ms_{75}Pg_{25}$
	Chlorite	F/FM = 0.64; Al/Si = 1.13	Chlorite	F/FM = 0.46 - 0.24; Al/Si = 0.77 - 0.9	Chlorite	F/FM = 0.61; Al/Si = 1.20
	Feldspar	$Ab_{99}An_1Or_0$	Biotite	F/FM = 0.5 - 0.21	Chloritoid	F/FM = 0.87
	Ilmenite	$"Fe"_{3.9}Mn_{0.3}Ti_{3.8}O_{12}$	Feldspar	$Ab_{92}An_7Or_1$	Garnet (core)	$Alm_{82}Sp_9Gr_4Py_5$
			Ilmenite	Not analyzed	Feldspar	$Ab_{80}An_{19}Or_{0.5}$
			and		Ilmenite	$Fe_{3.9}Mn_{0.06}Ti_{4.0}$
			Muscovite	$Ms_{75}Pg_{24}$	*and*	
			Chlorite	F/FM = 0.52; Al/Si = 1.10	Muscovite	$Ms_{79}Pg_{21}$
			Chloritoid	F/FM = 0.87	Chlorite	F/FM = 0.58; Al/Si = 1.17
			Feldspar	$Ab_{82}An_{15}Or_2$	Garnet (rim)	$Alm_{84}Sp_2Gr_7Py_6$
			Ilmenite	$Fe_{3.8}Mn_{0.2}Ti_{4.0}O_{12}$	Biotite	F/FM = 0.58
					Feldspar	$Ab_{70-80}An_{20-26}Or_{0.3}$
					Ilmenite	$Fe_{3.9}Mn_{0.02}Mg_{0.02}Ti_{4.01}O_{12}$
LOW-ALUMINA ASSEMBLAGES	Muscovite	$Ms_{86-98}Pg_{14-2}$	Muscovite	$Ms_{91}Pg_9$	Muscovite	$Ms_{91}Pg_5$
	Chlorite	F/FM = 0.67 - 0.39; Al/Si = 0.96 - 0.70	Chlorite	F/FM = 0.43; Al/Si = 0.98	Chlorite	Not observed
	Feldspar	$Ab_{100-93}An_{0-7}Or_0$	Biotite	F/FM = 0.41	Biotite	F/FM = 0.48 - 0.50
	Ilmenite	$Fe_{3.6}Mn_{0.3}Ti_{4.0}O_{12}$	Feldspar	$Ab_{99-96}An_{1-0}Or_{1-2}$	Garnet (core)	$Alm_{63}Sp_{18}Gr_{12}Py_7$
			Sulfide		(rim)	$Alm_{58}Sp_{18}Gr_{15}Py_8$
					Feldspar	$Ab_{48}An_{42}Or_{10}$
					Sulfide	

Table 2 (cont.)

Staurolite Grade		*Kyanite Grade*		*Sillimanite Grade*		*K-feldspar--Sillimanite Grade*	
Muscovite	$Ms_{80}Pg_{20}$		Not analyzed	Muscovite	$Ms_{89}Pg_{11}$	Garnet (rim)	$Alm_{58}Sp_{21}Gr_{7}Py_{14}$
Staurolite	F/FM = 0.83			Garnet (rim)	$Alm_{85}Sp_{3}Gr_{4}Py_{8}$	Biotite	F/FM = 0.32
Biotite	F/FM = 0.54			Biotite	F/FM = 0.62	Feldspar (plag)	$Ab_{56}An_{43-44}Or_{0-1}$
Garnet (rim)	$Alm_{81}Sp_{5}Gr_{5}Py_{8}$			Feldspar	$Ab_{79}An_{20-21}Or_{0-1}$	(alkali)	Not analyzed
Feldspar	Not analyzed			Ilmenite	$Fe_{3.88}Mn_{0.01}Mg_{0.02}Al_{0.03}Ti_{4.01}O_{12}$	Sillimanite	
Ilmenite	Not analyzed			Sillimanite			
and							
Muscovite	$Ms_{79}Pg_{20}$						
Chlorite	F/FM = 0.57; Al/Si = 1.08						
Staurolite	F/FM = 0.88 - 0.89						
Chloritoid	F/FM = 0.85						
Garnet (rim)	$Alm_{86}Sp_{2}Gr_{3}Py_{7}$						
Biotite	F/FM = 0.58 - 0.60						
Feldspar	$Ab_{79-88}An_{21-12}Or_{0-10}$						
Ilmenite	$Fe_{4.4}Mn_{0.01}Ti_{3.8}$						
Muscovite	Not analyzed	Muscovite	$Ms_{76}Pg_{24}$	Muscovite	$Ms_{96}Pg_{4}$	Not found	
Biotite	Not analyzed	Biotite	F/FM = 0.37	Biotite	F/FM = 0.55		
Staurolite	(Not observed)	Garnet (rim)	$Alm_{61}Sp_{21}Gr_{7}Py_{11}$	Feldspar	$Ab_{64}An_{34}Or_{1}$		
Garnet	Not analyzed	Kyanite		Sillimanite			
Feldspar	Not analyzed	Feldspar	$Ab_{76-80}An_{19-23}Or_{0-1}$				
Sulfide							

Road Log

Mileage

0 Intersection of Taconic Parkway and Rt. 55 at Freedom Plains, N.Y. Head south on the Taconic Parkway.

3 Turn west on Arthursburg Road. Between here and Stop 1 the Mt. Merino member of the Normanskill Fm. is exposed at a number of localities in the surrounding fields.

4.7 Stop 1 - Chlorite Grade (See Table 2)

Steep roadcuts along Arthursburg (Noxon) Rd. The purpose of this stop is to display typical pelitic lithologies at low metamorphic grade (i.e. chlorite zone). Similar lithologies, though not necessarily identical stratigraphy, constitute the metapelites to be visited at later stops.

The east end of the cuts consists of typical red and green slates and phyllites of the Indian River member of the Normanskill Fm. At the west end of the cut black slates, phyllites, and greywackes of the Mt. Merino member are exposed. The contact between these two units occurs just at the western end of the red Indian River exposures. Some faulting appears to have occurred along the contact and a later northwestward dipping reverse fault, with associated fracture cleavage, further complicates relationships. These roadcuts are part of a small erosional remnant of a larger allochthon whose principal exposure lies just north of Freedom Plains, N.Y. and is well exposed in the vicinity of James Baird State Park (Fig. 1).

Mineralogically the red phyllites and slates consist of hematite-chlorite-muscovite-plagioclase-quartz. The green lithologies consist of muscovite-chlorite-plagioclase-quartz. These differences imply a variation in oxidation state whose origin is not well understood. Gradations in color occur along strike of the beds and suggest that the variations may be secondary in origin.

The eastern portion of the roadcut consists of several relatively large (λ = 50-60'), upright folds on which are developed a multitude of parasitic chevron folds. Fold axes trend N30-50E and plunge NE at between 10° and 60° with most of the steeper plunges on the north side of the road. The style of folding is of the rounded, chevron type with minor folds reflecting the symmetry of the larger structures. Late flattening appears to have occurred. Associated with these folds is an axial planar crenulation cleavage that strikes N30-50E and dips steeply to the northwest. Close inspection shows that the cleavage intersects an earlier foliation that has been folded by the upright folds. The earlier foliation is usually subparallel to bedding but large intersection angles have been found.

Excellent weathered exposures, and a good overall perspective of the folds in the roadcut, can be found by climbing to the top of the cut.

At the western end of the cut the Mt. Merino slates and phyllites have undergone extensive kink folding with associated axial plane crenulation cleavage which strikes N40-50E and dips steeply to the west. Presumably these kinks are of the same generation as the chevron folds in the Indian River. Greywackes within the Mt. Merino have deformed by buckling rather by kinking.

Sedimentary structures can be seen within the greywackes and suggest that the section is not overturned.

Turn around and return east to Taconic Parkway.

6.4 Taconic Parkway. Turn north after crossing divide.

9.4 Junction with Rt. 55 east. Leave Taconic and proceed east on Rt. 55.

10.3 Roadcut in green phyllites of Everett Fm. (presumed allochthonous) on south side of road. This outcrop exhibits minor structure evidence for at least four phases of deformation. Kink folding and crenulation cleavage are abundantly developed.

10.7 Junction with Rt. 82 at Billings, N.Y. Continue east on Rt. 55.

11.2 Quartz-breccia fault zone.

13.0 Turn north on Wingdale Road.

13.8 <u>Stop 2</u> - <u>Biotite Grade</u> (see Table 2)

Small roadcut in black Walloomsac slates. The slates are highly graphitic and often contain large amounts of pyrite. A strong N20W, 60E cleavage pervades the rocks and is related to N20W minor folds in the outcrop. These folds rotate an earlier foliation. Mineral phases present in the rock are: biotite-chlorite-muscovite and plagioclase-quartz-ilmenite.

The principle reason for stopping at this outcrop is that biotite is developed macroscopically and is easily visible with a hand lens. Here we are very close to the biotite isograd. Note that the biotite flakes grow across the planes of foliation. Be careful to distinguish flakes of biotite from ilmenite grains.

14.5 Large roadcuts in black, graphitic, sulfidic Walloomsac slates. Vein quartz is abundant in the outcrop. Proceeding down the hill, we enter the Clove Valley which is underlain by Wappinger carbonates of the shelf sequence.

15.2 Proceed past small traffic circle and continue eastward up hill (Dutchess County 31 or Blueberry Hill Road). Going up the hill note the cuts on the south side of the road.

16.1 <u>Stop 3</u> - <u>Garnet Grade</u> (see Table 2)

Pull off into small parking area on south side of road.

(a) Walk back down hill to examine cuts passed as we drove up hill. These consist of black biotite rich schists and cleaved metagreywackes. The observer is asked to compare these lithologies with the Mt. Merino seen at Stop 1. The principal foliation is N60E and dips 45°S.

In coming eastward from Stop 2 we have passed over the <u>garnet</u> isograd. At this locality garnet is sparsely developed in the more westerly (downhill) outcrops of black, graphitic biotite schists. The mineral phases in these rocks consist of garnet-chlorite-biotite-muscovite-feldspar-quartz (Fig. 4a). Proceeding uphill, the amount of graphite decreases while quartz increases, and the rocks begin to resemble greywackes. Within these units garnet is principally developed in thin beds which probably represent pelitic members in a turbidite sequence.

It has not been determined whether these rocks are allochthonous or autochonthonous. They are shown on the New York State Geological Map (1973) as Austen Glen greywackes. This designation, or an assignment to the Mt. Merino, would strongly imply that they are allochthonous. Approximately 1/4 mile south of here the metapelites are found overlying either Poughquag quartzites or the lowermost, quartzite rich, portion of the Stissing. If the rocks are not allochthonous, then the Middle Ordovician unconformity bevelled to the deepest portions of the shelf here, while 1.5 miles to the west the Balmville and Walloomsac rest on the Copake Limestone which occurs at the top of the Wappinger Group. This is by no means an impossible situation, but serves to emphasize the nature of the unresolved structural problems in the area.

(b) Return to parking area and walk north along the old dirt road to the north of the highway. After approximately 200' climb up to the exposures on the east side of the road. These small ledges show an exceptional development of chloritoid. Black chloritoid grains of up to 1/8" in length can be seen growing in seemingly random orientation. Microscopically the chloritoids are clearly younger than the principal foliations but are deformed by kinking and crenulation.

The mineral assemblage in these rocks consists of garnet-muscovite-chlorite-chloritoid-feldspar-quartz. As shown in Fig. 5a, this assemblage is the result of a more aluminous bulk composition than in the rocks at 3a. Here biotite is absent and is separated from chloritoid in an AKFM projection by the garnet-chlorite tieline (Fig. 5a).

At least two major foliations are present in the outcrop. An early N30E, 40S foliations appears to be related to small, attenuated isoclinal folds defined by thin quartz stringers. This foliation is generally parallel to compositional banding. The dominant foliation in the rock appears to be later and trends N80E, 25S. This foliation is axial planar to a sharp disharmonic fold exposed just above the ledge which best displays the chloritoid grains. Note that this fold folds an earlier foliation.

(c) Return to the paved highway and walk east up the hill examining the interlayered schists and quartzose rocks. Chloritoid is still present in some of these units but grain outlines are not as sharp as at 3b. This may be the result of the onset of a chloritoid consuming reaction. Biotite and chloritoid are still mutally exclusive and remain separated by the tie line garnet-chlorite. Although chloritoid is still present in some layers, most of the schists consist of garnet-chlorite-biotite-muscovite-feldspar-quartz. These lithologies are similar to the rocks at 3a, and chloritoid is unable to form because the bulk compositions are not sufficiently rich in aluminum (Fig. 5a). This serves to emphasize the control of rock chemistry on the development of chloritoid in the area.

17.2 Turn south on Pleasant Ridge Road.

17.9 Turn west on Still Road.

18.5 Stop 4 - Staurolite Grade (see Table 2)

Low, rounded outcrop on the north side of the road. These rocks are approximately along strike (N20E, 30E) with the chloritoid bearing schists at Stop 3b. Here we are at somewhat higher grade and staurolite is developed in thin section. The overall mineral assemblage in these rocks is garnet-staurolite-chloritoid-muscovite-chlorite-biotite-feldspar-quartz (Fig. 5b). The presence of five ferromagnesian phases is clearly in violation of the phase rule and this assemblage cannot be in equilibrium. This locality marks the lowest grade at which staurolite is found and the highest grade at which chloritoid is stable. Note the coexistence of biotite and chloritoid both of which are visible in hand specimen. Clearly the tie-line chlorite-garnet is in the process of being broken by biotite-chloritoid. Simultaneously chloritoid is participating in a staurolite forming reaction.

18.7	Dead end and turn around. Proceed back east on Still Road.
19.5	Pleasant Ridge Road. Turn south.
21.5	Y intersection with Gardner Hollow Road. Bear right (west).
21.5	Turn left to stay on Pleasant Ridge Road.
22.7	Junction with Rt. 55. Turn east. Note roadcuts of Poughquag Quartzite on the south side of Rt. 55.
24.4	Turn north onto old Rt. 55.
26.3	Wilkinson Hollow Road.
27.3	Enter Edward R. Murrow Park for lunch. The exposures in the park are Balmville limestones and Walloomsac schists. Following lunch turn back west onto old Rt. 55.
28.3	Wilkinson Hollow Road. Turn north.
28.9	Stop 5 - Kyanite Grade (see Table 2)

Park at dead end and walk up the dirt road, past a house, and continue along the footpath. The valley here is underlain by Balmville Limestone. After approximately 1/4 mile the path crosses beneath a power line. Turn east up the hill to exposures of staurolite-garnet-biotite-muscovite-quartz-feldspar schists (Fig. 5c). These rocks are typical of staurolite rich schists in the region. Good penetration twins of staurolite can be found. Kyanite appears to be absent at this locality, and this is probably due to differences in bulk rock composition (Fig. 5c).

The outcrop here contains several large, recumbent isoclinal folds. One of these is dominant and its axial region is exposed near the top of the outcrop. The axial plane strikes N60E and dips 20°S while the axis trends N30W and plunges 10°N, however, the exposure may be out of place. An earlier foliation, defined by micas, has been folded by this structure.

Return to cars, turn around, and proceed south on Wilkinson Hollow Road.

29.5 Turn west on old Rt. 55.

31.4 Intersect new Rt. 55. Turn east and head uphill through Precambrian gneisses of the Hudson Highlands.

32.0 Contact between the Precambrian and black, rusty Paleozoic schists (Walloomsac?). Balk (1936) mapped this contact as a reverse fault. Ratcliffe (pers. comm.) has suggested that the absence of the carbonate section may be due to the lower Middle Ordovician unconformity. Minor structures are consistent with Balk's interpretation.

32.6 Stop 6 - Kyanite Grade (see Table 2)

The rocks in these long roadcuts have been mapped as Walloomsac schists (N.Y. State Geological Map, 1973). Whether they are, or not, is open to question. Regardless of stratigraphic uncertainty, the lithologies are dominantly pelitic with biotite rich schists predominating. Quartzose and granular quartzofeldspathic layers and lenses are interlayered with the schists and serve to define early isoclinal folds. The dominant cleavage trends N30-40E and dips approximately 50°S. This cleavage is axial planar to tight northeast trending folds which fold the earlier isoclinal folds whose general trend is also northeast. An earlier foliation is associated with these isoclines. In places the second generation folds have been flattened into isoclines. Minor folds associated with these give opposing senses of rotation as the roadcuts are traversed along their length and suggest that the entire roadcut has been telescoped by the second generation folds. A third of open N-S folds is present and associated with kinking and crenulation cleavage in the rock.

Mineralogically the schists generally contain biotite-garnet-kyanite-muscovite-feldspar-quartz. The kyanite appears as 1/8" - 3/4" blue blades growing without orientation within the schists, and is particularly concentrated within more pelitic layers, many of which have thickened on the noses of folds. This gives rise to pod like areas that are extremely rich in kyanite. These can be examined to best advantage on the top of the roadcut where weathering has made the kyanites most visible. The metamorphic grade observed here is the same as at Stop 5 but staurolite is rarely observed in these rocks. This may be attributed to bulk compositional differences between the two localities (Fig. 5c). The rocks here are more magnesian than at Stop 5 and staurolite is generally excluded from the phase assemblage.

In addition to kyanite rich layers certain quartzose bands are extremely rich in garnet. Hornblende bearing pods are also present and represent more calcic bulk compositions in the original sediment.

Biotite from a biotite-kyanite assemblage here gives an $^{40}Ar/^{39}Ar$ plateau age of 414 million years.

33.5 Roadcuts in the Walloomsac black schists. A sharp anticline brings the Balmville Limestone to the surface near the east end of the cut. This outcrop is situated near the hinge of the Harlem Valley Syncline.

34.1 Roadcuts in the Balmville Limestone. Here the Balmville is directly overlain by Walloomsac black schists.

34.3 Walloomsac calc-silicates and Balmville Limestone. The Harlem Valley can be seen directly ahead. We are now proceeding into the overturned, eastward dipping, limb of the Harlem Valley Syncline.

34.7 Calcitic marbles of the upper portion of the Wappinger Group are exposed to the south of the highway.

35.2 Stop 7 - Very large roadcuts in the Briarcliff Dolostone. This stop is the same Stop 7 in McLelland and Fisher (this volume), and the structure of the cut is discussed in that article.

Petrologically this stop is of interest because it affords the opportunity to examine the development of calc-silicates at grades approaching the first--sillimanite isograd. Throughout the roadcut diopside, tremolite, and phlogopite are abundantly developed in the appropriate lithologies and are best seen on the weathered surface at the top of the roadcut. The most noteworthy example of calc-silicate development occurs close to the top of the roadcut near its eastern terminus. Here a two foot wide layer consists almost entirely of extremely coarse tablets, blades, and rosettes of white tremolite. The layer can be followed for well over 50 feet. In adjacent layers diopside tablets appear to be the only calc-silicates developed. Presumably this represents a very steep gradient in P_{H_2O} and a local system effectively closed with respect to the water migration across layers.

35.8 Low outcrop of Briarcliff Dolostone on the north side of Rt. 55. This outcrop contains outstanding examples of perfectly formed diopside tablets.

36.1 Interchange for Rt. 55 and Rt. 22. Continue to 22/55 N.

36.5 Enter Rt. 22/55 North.

36.8 Traffic light. Turn east onto Quaker Hill Road. Continue along this road for 2.6 miles. Markers include the "Glen Arden Farm" and a sharp, hairpin turn going up Tracy Hill.

39.4 Stop 8 - Sillimanite Grade (See Table 2)

Roadcuts in coarse, muscovite rich schists. Large garnets are developed. Sillimanite is present in this outcrop but has not been recognized in hand specimen. Tourmaline bearing pegmatities occur and suggest the onset of anatexis (Table 2).

Displayed within the roadcut are numerous examples of disharmonic folding in which the more competent quartzo-feldspathic units have broken and rotated. Early isoclinal folds may be seen. Many of these have attenuated limbs. Rootless isoclinal folds occur.

End Road Log